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HYPEREUTECTIC ALUMINUM-SILICON ALLOYS PRODUCED BY POWDER METALLURGY TECHNIQUES

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Nuclear and Powder Metallurgy Section

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ABSTRACT

Three hypereutectic aluminum-silicon alloys containing 25%, 35% and 45% Si were prepared using powder metallurgy techniques. Pre-alloyed powders, which were produced by atomization of the molten alloys, were fabricated by hot pressing and extruding to give material with density close to theoretical.

The main object of the investigation was to determine if atomization of the alloys would result in refinement of the primary silicon, and metallographic examination of the powders showed that this was accomplished, although additions made to the melts assisted in such refinement.

Raising the silicon content resulted in a decrease in coefficient of thermal expansion and an increase in wear resistance.

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INTRODUCTION

Much work has been done in recent years on the development of hypereutectic aluminum-silicon casting alloys, primarily for use in the automotive industry [1-5]. These alloys have low density, high strength-to-weight ratio, good wear resistance, and low coefficient of thermal expansion, but they suffer from the disadvantage that the primary silicon phase solidifies over a wide temperature range and forms large particles that tend to segregate, resulting in inferior mechanical properties and poor machinability. Significant refinement of the primary silicon phase has been obtained by the use of nucleation catalysts, improved melting practices, and fast freezing rates, but further refinement continues to be sought.

Consideration of the problem suggested that refined hypereutectic aluminum-silicon alloys might be made by powder metallurgy techniques. By using pre-alloyed atomized powder, not only could recommended melting practices and nucleation catalysts be used, but the rapid freezing rate of each powder particle would induce refinement of the primary silicon phase. Another attractive feature, unique to the powder metallurgy process, would be that the size of the powder particles would be a limiting factor on the size of the primary silicon phase, and by sieving out the larger particles, powder fractions containing a fine dispersion of the silicon phase might be obtained.

This paper describes the powder metallurgy techniques used to prepare some hypereutectic aluminum-silicon alloys. The properties obtained

from such material are compared with those reported in the literature for hypereutectic aluminum-silicon alloys prepared by conventional methods of melting and casting.

EXPERIMENTAL PROCEDURE

Preparation of Alloy Powders

Pre-alloyed powders with nominal silicon contents of 25%, 35% and 45%, were prepared by alloying aluminum (99.99% purity) and silicon (99.10% purity) in 800 g melts made in a silicon carbide crucible coated with zirconia and heated in a resistance furnace. In order to dissolve the silicon, the alloying temperature was raised with increasing silicon content, being 825°C (1520°F), 930°C (1705°F) and 1200°C (2190°F) for the Al - 25% Si, Al - 35% Si and Al - 45% Si alloys, respectively. The melts were treated with degassing tablets and then 0.03% P (in the form of 7% phosphorus copper brazing rod) and 1.0% Mg (99.99% purity) were added to refine the primary silicon phase; this melt treatment is based on that found by other investigators [4] to be effective in refining the primary silicon. The melts were next skimmed and poured at the above temperatures into an apparatus in which the molten alloy was atomized by jets of compressed air and water [6]. This procedure was used in all cases except for one melt of the Al - 25% Si composition, which was made without additions of phosphorus or magnesium. The resulting powders were dried and sieved, and the -100 mesh fraction was retained for further processing.

Compacting, Extruding and Heat Treating

The alloy powders were cold pressed at 30 tons/sq in. into billets 2 in. diameter by 3 in. long, and these billets were then hot pressed at 30 tons/sq in. and 350 to 400°C (660 to 750°F) for 10 min. The hot-pressed billets were re-heated to 350 to 400°C (660 to 750°F) for 30 min and extruded at 400°C (750°F) to give 0.5 in. diameter rod. The Al - 25% Si and Al - 35% Si alloys extruded without difficulty at 400°C (750°F) but the Al - 45% Si alloy could not be extruded at this temperature. Except where indicated otherwise, the tests reported for the Al - 25% Si and Al - 35% Si alloys were carried out on as-extruded material, and the tests reported for the Al - 45% Si alloy were carried out on hot-pressed material.

The effect of heat treatment on the properties of the three alloys (except Al - 25% Si without refining additions) was investigated by heating them to 535°C (995°F) for 6 hr and quenching into boiling water, followed by ageing at 200°C (390°F) for times of up to 4 hr.

Testing and Examination

Tensile tests were carried out on all three compositions, the test specimens being 1 in. long with a gauge length of 0.447 in. and a gauge diameter of 0.126 in. Brinell hardness surveys were also made on each composition.

The coefficient of thermal expansion between 20°C (70°F) and 300°C (570°F) was determined for the three alloys. The dilatometer specimens were 2.56 in. long by 0.312 in. diameter for the Al - 25% Si and Al - 35% Si alloys, and 1.57 in. long by 0.129 in. diameter for the Al - 45% Si alloy.

The density of the alloys was determined by the method described in ASTM Designation B311-58, which is based on the displacement of water by the test specimen.

The wear resistance of the alloys was assessed by determining the weight loss incurred by a 1/8 in. diameter by 1/2 in. long pin of the material after the end of the pin had been in dry contact with a rotating cast iron disc; the conditions of the test were 1,000 psi and a speed of 200 in. per min for 1 hr. For comparison purposes, besides testing the three hypereutectic aluminum-silicon alloys, tests were also carried out on a commercial casting alloy with a nominal silicon content of 11.5% and sodium-modified.

Microexamination was carried out on the powders, and on the billets before and after extrusion.

Samples for chemical analysis were taken from the -100 mesh powder prior to pressing.

RESULTS

Alloy Composition

The results of the chemical analysis of the -100 mesh powders are listed in Table 1.

TABLE 1

Alloy Composition

Alloy	Si, %	P, %	Mg, %	Cu, %
Al-25% Si	24.5	0.007	1.04	0.36
Al-25% Si*	24.1	-	-	-
Al-35% Si	33.0	0.005	1.14	0.37
Al-45% Si	44.0	0.008	1.05	0.36

* No P, Mg, or Cu additions

Silicon Refinement

The atomized powders were of irregular shape, and contained a wide range of particle sizes. Figures 1, 2 and 3 illustrate the size, shape and microstructure of the powders produced from the 25%, 35% and 45% Si alloys to all of which phosphorus and magnesium had been added to refine the primary silicon phase. The primary silicon phase shows as grey particles. It can be seen that there is a slight increase in the size of the silicon particles with increasing silicon content, although the particles are fairly uniform in all cases and none of them is very large even in the coarser

powder particles.

The 25% Si alloy powder, which had no phosphorus or magnesium additions, contained, in general, a fine dispersion of silicon, but the occasional large particle was present, as illustrated in Figure 4.

As already mentioned, only the -100 mesh fraction of the powders was processed and tested, and Figures 5, 6 and 7 illustrate the appearance of this fraction for the 25%, 35% and 45% Si compositions with refining additions. The 25% Si powder to which no refining additions were made was similar to Figure 5, the large silicon particles having been eliminated by sieving as they were present mainly in the alloy particles of +100 mesh size.

Figure 8 illustrates the transverse microstructure of the 45% Si alloy in the as-extruded condition (a small piece of extruded material was available for microexamination) and this structure is also typical of 25% Si and 35% Si alloys. The microstructures of the extruded rods in the longitudinal direction were similar to those in the transverse direction.

Table 2 gives the size of the primary silicon particles in the extruded and (for 45% Si only) hot-pressed materials.

TABLE 2

Size of Primary Silicon Particles

Alloy	Condition	Average Size of Coarser Particles (Microns)	Size of Largest Particles (Microns)
Al-25% Si	As-extruded	5	17
Al-35% Si	As-extruded	5	17
Al-45% Si	As-extruded	5	20
Al-45% Si	Hot-pressed	10	50

Heat Treatment and Mechanical Properties

The results of the mechanical tests are listed in Table 3.

TABLE 3

Mechanical Properties of Hypereutectic Al-Si Alloys

Alloy	Condition*	UTS (kpsi)	0.2% YS (kpsi)	% El. 4 $\sqrt{A}$	BHN (500 kg/30 sec)
Al-25% Si	As-extruded	33.2	22.5	8	86
Al-25% Si	H.T. Aged 200°C (390°F) 1 hr	31.9	30.1	2	60.5
Al-25% Si	H.T. Aged 200°C (390°F) 4 hr	32.2	30.2	2	63
Al-25% Si**	As-extruded	21.4(2)	15.0(2)	6(2)	42
Al-35% Si	As-extruded	32.1(1)	31.3(1)	2(1)	67
Al-35% Si	H.T. Aged 200°C (390°F) 1 hr	32.0(2)	30.8(1)	2(2)	61
Al-35% Si	H.T. Aged 200°C (390°F) 4 hr	29.0	ND	0	64.6
Al-45% Si	Hot pressed	39.9(2)	ND	0(2)	114
Al-45% Si	H.T. Aged 200°C (390°F) 1/2 hr	28.1	ND	0	132
Al-45% Si	H.T. Aged 200°C (390°F) 4 hr	33.7(2)	ND	0(2)	126

* H.T. = Heat treated at 535°C (995°F) for 6 hr then quenched into boiling water.

** = No refining additions.

ND = Not determined.

The tensile results listed in Table 3 are the averages of three tests except where indicated otherwise by the numbers in brackets. The Brinell hardness results are the averages of at least two determinations.

Thermal Expansion

The results of the thermal expansion coefficient measurements are listed in Table 4, which also includes, for comparison purposes, values quoted elsewhere for Al - 21% Si[4], Al - 5% Si[7] and Al - 12% Si[7] casting alloys, and for cast iron[8].

TABLE 4

Thermal Expansion Coefficients for Al-Si Alloys and Cast Iron

Alloy	Coefficient (in./in./°C x 10^6)	Temperature Range	
		°C	°F
Al-25% Si	17.44	20-300	70-570
Al-35% Si	15.23	"	"
Al-45% Si	14.51	"	"
Al-21% Si[4]	17.89	0-300	32-570
Al-21% Si[4]	18.94	"	"
Al- 5% Si[7]	24.0	20-300	70-570
Al-12% Si[7]	21.5	"	"
Cast Iron[8]	11.5-12.7	20-400	70-750

Density

The results of the density determinations carried out on the Al - 25% Si and Al - 35% Si extruded rods, and the Al - 45% Si hot pressed billet are given in Table 5.

TABLE 5

Density of Al-Si Alloys

Alloy	Density (g/cc)
Al-25% Si	2.60
Al-35% Si	2.50
Al-45% Si	2.48

Wear Tests

The wear test results listed in Table 6 are each the average of three tests. all of which showed good agreement for each alloy. During testing, the casting alloy and - to a considerably less extent - the Al - 25% Si alloy, developed a burr that was considered as metal lost to the test specimen and in these cases the specimens were deburred prior to weighing. The Al - 35% Si and Al - 45% Si alloy specimens showed no flowed metal on completion of the test.

TABLE 6

Results of Wear Test on Al-Si Alloys

Alloy	Weight Loss After 1 hr ($g \times 10^4$)
Al-11.5% Si (casting alloy)	167
Al-25% Si	132
Al-35% Si	98
Al-45% Si	86

DISCUSSION

As mentioned in the "Introduction", an inherent advantage of the powder metallurgy technique as applied to production of hypereutectic aluminum-silicon alloys is that the fineness of the alloy powder is a factor that can control the size of the particles of primary silicon.

Another advantage of the powder metallurgy process is that parts can be pressed to the desired size and shape with little or no subsequent machining. In the present work, most of the evaluation and testing were done on extruded material but the results of the tests on the hot-pressed Al - 45% Si alloy indicate that useful properties can be obtained by hot pressing alone. The latter method would be advantageous for producing to shape small components in which light weight, wear resistance, and low thermal expansion are desirable.

Silicon Refinement

The main purpose of this investigation was to study the effect of the

rapid cooling produced by atomization of the molten metal on the size and distribution of the primary silicon phase in hypereutectic aluminum-silicon alloys. The melting practice used in preparing all melts (except one Al - 25% Si alloy melt) was based on that used by Urdea and Telang [4] to refine the primary silicon.

In each of the alloy powders made, the primary silicon phase was refined, as shown by the photomicrographs, Figures 1 to 4. However, comparison of the microstructures of Al - 25% Si with refining additions (Figure 1) and without refining additions (Figure 4) shows that the former contains the finer and more uniform silicon particles, indicating that, although the atomizing process itself effects considerable refinement of the silicon, further refinement results from the melt additions. Comparison of Figures 1, 2 and 3 also shows that the silicon particle size increases with silicon content and that the oblong particles become more numerous as the silicon content increases.

Separation of the -100 mesh fraction of the powders resulted in further refining as most of the larger silicon particles were present in the +100 mesh powder fraction; this result can be seen by comparing Figures 1, 2 and 3 with Figures 5, 6 and 7 respectively. Consolidation and extrusion of the powders resulted in further reduction in the size of the primary silicon (see Figure 8).

These hypereutectic aluminum-silicon alloys suffer from the disadvantage that high temperatures are required during alloying and casting, and it is possible that such alloys might better be prepared by mechanical

mixing of very fine powders (preferably sub-micron in size) of aluminum (or hypoeutectic or eutectic Al-Si alloys) and silicon, followed by hot pressing.

Mechanical and Physical Properties

The tensile strength of the as-extruded and hot-pressed alloys (see Table 3) was not significantly improved by heat treating. Increasing the silicon content from 25% to 45% had little effect on the mechanical properties apart from lowering the ductility and increasing the hardness. The comparatively low strength of the Al - 25% Si composition without refining additions was due to the absence of magnesium and copper.

As Table 4 shows, increasing the silicon content of the alloys results in a continuous decrease in the coefficient of thermal expansion, which is about 25% less for the 45% Si alloy than for a 21% Si casting alloy.

Based on the calculated densities of the three compositions produced, the densities of the Al - 25% Si, Al - 35% Si and Al - 45% Si alloys were 100%, 97% and 98% of theoretical, respectively. These results were confirmed by the appearance of the microstructures.

The wear test results (Table 6) show that weight loss decreases with increasing silicon content. Thus, the weight loss for the Al - 45% Si alloy was only 51.5% of that for the 11.5% Si casting alloy. However, a comparison cannot be made between the casting alloy and powder alloys on the basis of silicon content alone because the latter contained more copper and magnesium, which would strengthen the matrix and improve wear resistance. The effect of silicon in improving wear resistance can better be seen by

comparing the results for the three powder alloys all of which had the same nominal composition for the matrix metal; thus, the weight loss for the 45% Si alloy was 65% of that for the 25% Si Alloy.

It is not presumed that the wear test results would apply to any service condition, but it seems reasonable to conclude from them that there is a significant improvement in wear resistance in going from 25% Si to 45% Si.

No machining tests were carried out on the alloys, but they machined satisfactorily during preparation of the test specimens.

CONCLUSIONS

(1) Refined aluminum-silicon alloys with up to 45% Si can be produced by powder metallurgy methods.

(2) Increasing the silicon content from 25% to 45% produces no significant change in tensile strength, but lowers the ductility and increases the hardness.

(3) The coefficient of thermal expansion is progressively decreased with increasing silicon content, and the Al - 45% Si alloy has a thermal expansion about 25% less than that of the Al - 21% Si casting alloy.

(4) Densities close to theoretical can be obtained by hot compaction and extrusion of hypereutectic aluminum-silicon alloys.

(5) Wear resistance improves as the silicon content is increased from 25% to 45%.

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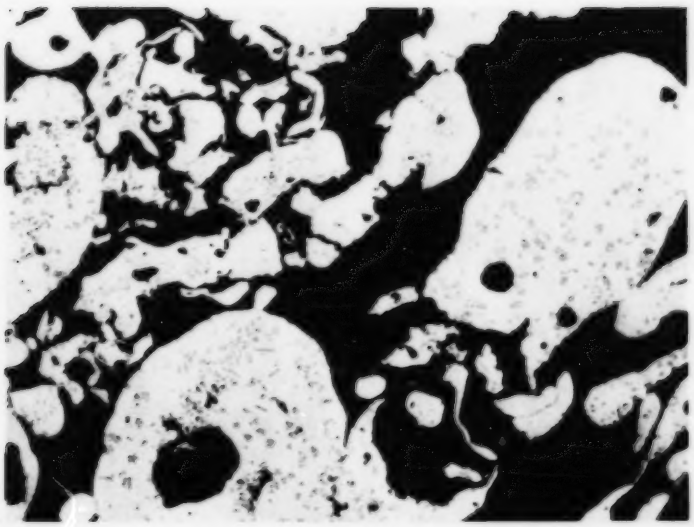

X100

Figure 1. Al-25% Si Powder. (Before sieving).

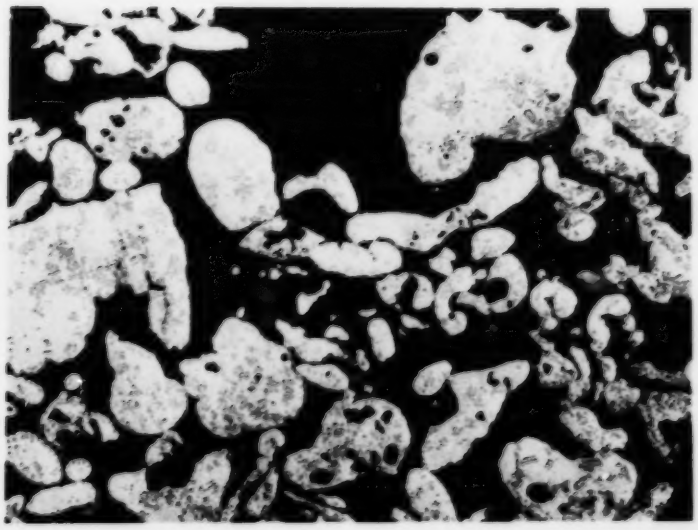

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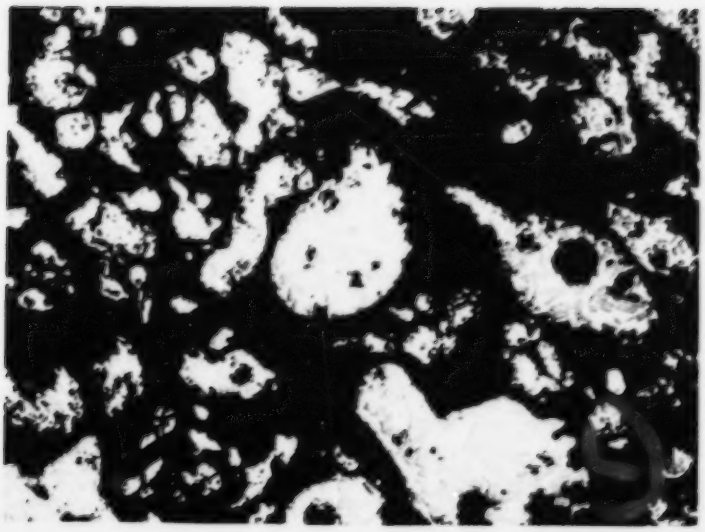
Figure 2. Al-35% Si Powder. (Before sieving).



X100

Figure 3. Al-45% Si Powder. (Before sieving).

X100

Figure 4. Al-25% Si Powder. No refining additions. (Before sieving).

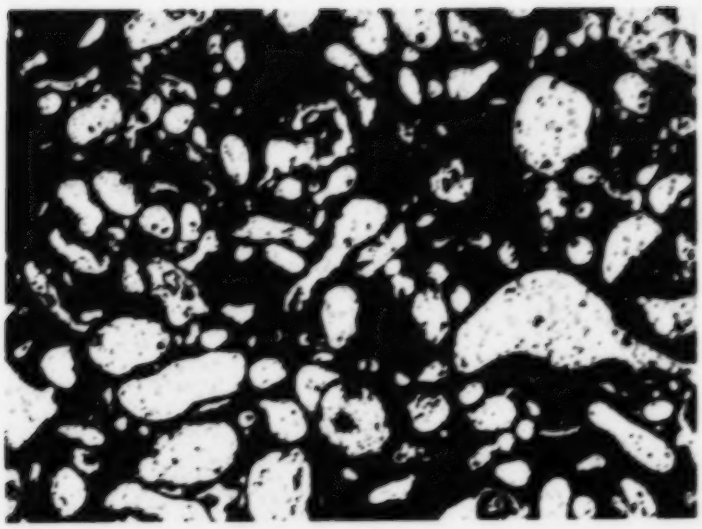


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Figure 5. Al-25% Si Powder, -100 mesh.

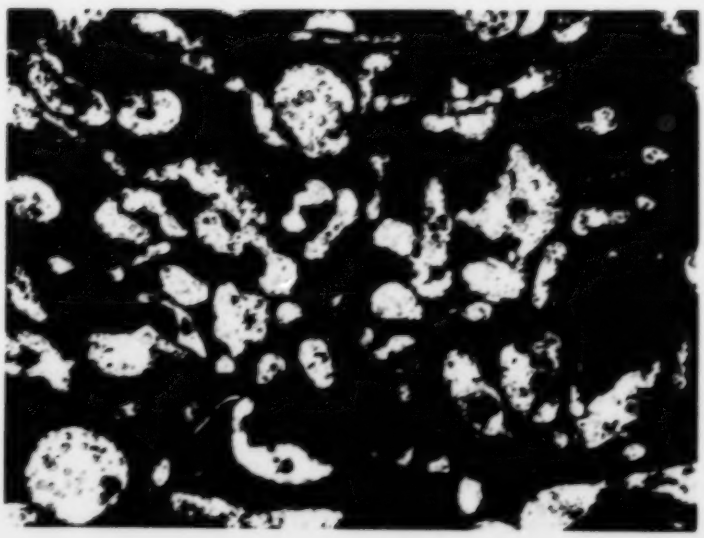

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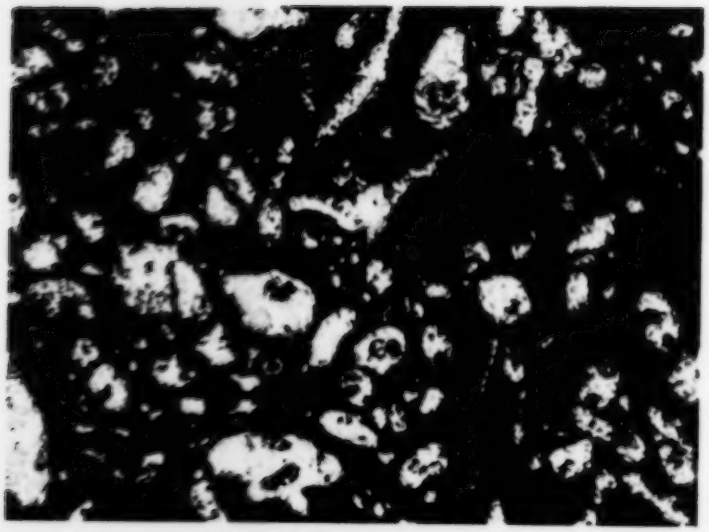
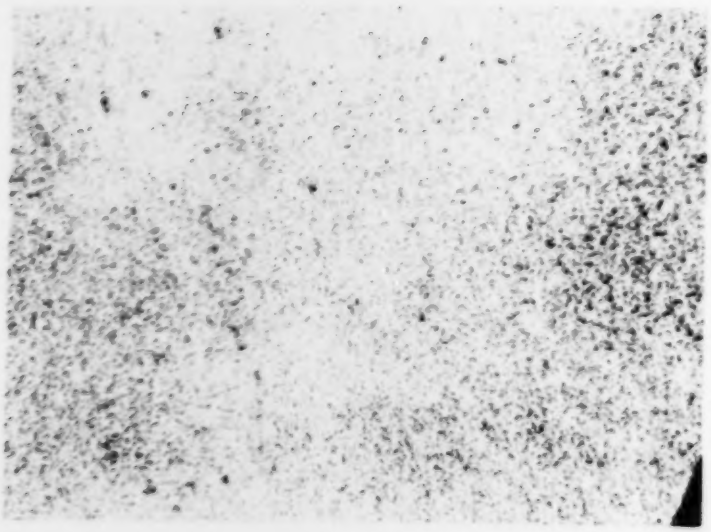
Figure 6. Al-35% Si Powder, -100 mesh.



X100

Figure 7. Al-45% Si Powder, -100 mesh.



X100

Figure 8. Al-45% Si Extruded Rod. (Transverse section).